

Deformation of Coated Stainless Steel Tubes from Reflected Detonation

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1 Introduction

Piping systems are frequently employed to transport flammable gaseous mixtures of fuel and oxygen. Should an ignition event occur and the corresponding flame undergo deflagration-to-detonation transition (DDT), the high pressures resulting from the gaseous detonation may plastically deform or even rupture the containment vessel. Hence it is imperative to understand the pressure loadings created by gaseous detonations so that adequately strong piping systems may be designed. In this work, we examine the case of a gaseous detonation undergoing normal reflection. As discussed in Shepherd et al. [1], the case of normal reflection results in the largest internal pressures for a mixture of given initial pressure and thus is where failure will most readily occur. Experimental and computational work has been performed for the case of reflecting detonation on stainless steel tubes for two regimes of initial pressure: Low initial pressures ($P_0 = 50$ kPa) for which the containment tube underwent purely elastic deformation, and medium initial pressures ($P_0 = 200$ or 300 kPa) for which the containment tube plastically deformed. Were the initial pressure to be further increased the containment tube would certainly rupture, but as the facility is not currently able to contain blast waves this case was avoided.

The core physics of the reflected detonation are described in Shepherd et al. [1]. The incident detonation may be well approximated as a planar, one-dimensionally propagating wave as described in detonation textbooks [2, 3]. The detonation induces a rise in fluid pressure and velocity as given by the Chapman-Jouguet solution. When this fluid impacts an end-wall, it stagnates and produces an additional rise in pressure. The motion of the tube wall to this pressure loading has been well studied in our laboratory. Beltman and Shepherd [4] examined the elastic motion of the tube wall to the detonation. Chao and Shepherd [5] examined failure of aluminum tubes. In more recent work, Karnesky et al. [6] explored the elastic and plastic response of mild steel tubes to reflected detonations. Here we expand upon that work and examine stainless steel tubes of identical geometry. The high strain-rate response of stainless steel is better understood than mild steel and hence stainless steel was chosen so that computational models may better replicate the experimental results.

Also of interest to our research group is developing effective measures to lessen the deformation from a detonation of given strength. In previous work [7–9] polymer coatings have been shown to mitigate plastic deformation resulting from blast loadings. Thus it is logical to examine polymer coatings to see if they are able to effectively mitigate plastic deformation for detonation loadings. To this end, we have coated the exterior of some of the stainless steel tubes with a polyurea coating to test the ability of polyurea to mitigate plastic deformation.

2 Experimental Description

A detonation tube similar to that described in [6] was used to study stainless steel tubes deformed by reflected detonation loading. The tube was formed by coupling a thick-walled (25.4 mm wall thickness) driver tube of 1.2 m length and 127 mm inner diameter with a thin-walled (1.65 mm wall thickness) 304L stainless steel welded specimen tube, also of 1.2 m length and 127 mm inner diameter, via an O-ring gland seal as shown in Figure 1. The entire tube was initially evacuated to pressure below 50 mTorr

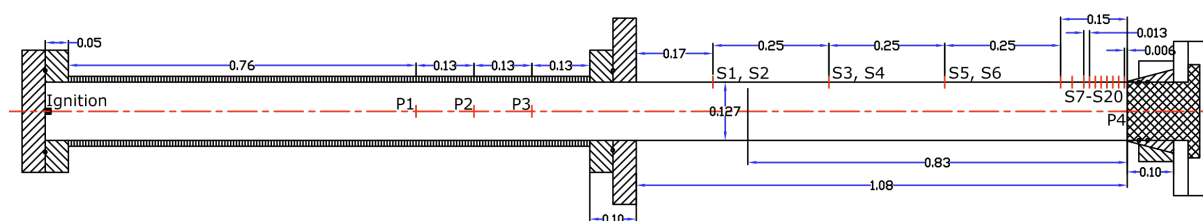


Figure 1: Detonation tube schematic with dimensions in meters.

before being filled via the method of partial pressures with stoichiometric ethylene-oxygen to initial pressure of either 50, 200, or 300 kPa. Ignition occurred in the left-hand side of the driver tube, and paddle-shaped obstacles located in the driver tube ensured early DDT. Three PCB 113A24 pressure gauges placed in the wall of the driver tube monitored the detonation pressure profile and allowed us to guarantee that a well-formed detonation propagated into the specimen tube.

The highest pressures and thus the largest material deformation occurred at the reflecting end of the specimen tube (the right-hand side of Figure 1) where the fluid induced into motion by the detonation stagnated. As we were interested in modeling the extent of this deformation, it was imperative that a well-defined boundary condition existed at this reflecting end. To accomplish this, a solid aluminum plug was designed to fit inside the stainless steel specimen tube with an O-ring gland seal, and a hardened tool steel collet was made to fit over the outside of the tube such that the end of the external collet coincided with the end of the internal plug. To keep this assembly fixed, a collet ring was secured to a steel plate with eight 9/16"-18 bolts with minimum preload of 125 N-m to result in a clamping force in excess of 100 kN, and this collet assembly was securely fastened to a 2700 kg mass. This assembly ensured the well-defined reflecting-end boundary condition we desired.

In order to measure the time-resolved material deformation, up to twenty strain gauges were glued to the specimen tube. Precise gauge location, orientation, and type depended upon experiment, but in general up to 20 strain gauges were employed, and the majority of the strain gauges were placed in the vicinity of the reflecting end and were oriented in the circumferential or "hoop" direction so that the deformation of the tube in this region of interest could be recorded. In addition to the strain gauges, one PCB 113B23 pressure transducer was placed in the center of the reflecting end where the peak pressures were expected. The pressure profile at the tube wall was not measured because it was not possible to mount pressure gauges in the specimen tube without altering the deformation. All strain and pressure data was recorded at 2.5 MHz during the detonation event.

Data for six tubes (tubes 9–10 and 13–16) is presented herein. All tubes were first subjected to a detonation of initial pressure 50 kPa, and purely elastic deformation was induced in the tube walls. These elastic experiments allowed us to both test that the metrology equipment was functioning properly and to analyze purely elastic deformation. After the elastic experiment, the experiment was reset and all tubes were then deformed plastically by a detonation of either initial pressure 200 kPa or initial pressure 300 kPa. Tubes 9, 13, and 15 were each subjected to 2 bar initial pressure detonations, and Tubes 10, 14, and 16 were each subjected to 3 bar initial pressure detonations. Tubes 9 and 10 were benchmark cases that were not coated with polyurea. Tubes 13 through 16 were spray-coated with SPI Ultra Bond-100 Polyurea, and the deformation caused by the reflected detonation was compared against tubes 9 and 10. Except for density, which was measured, the physical properties for the polyurea were supplied by the vendor and are given in Table 1.

The nominal coating thicknesses are reported in Table 2. These experiments were a preliminary investigation into the damage mitigation properties of polyurea for internal reflected detonation loading, and thus strict tolerances on the thicknesses were not imposed, with the maximum variance being 0.35 mm. For the cases of tubes 13 and 14, which had both strain gauges and polyurea coating present, the gauges were first glued to the stainless steel wall of the tube and then the polyurea was spray-applied. In all cases, the outer diameter was measured with an outside micrometer after each experiment that resulted in plastic deformation.

Table 1: Polyurea physical parameters.

Density	100% Elastic Modulus	Minimum Tensile Strength	Minimum Elongation
952 kg/m ³	4.6 MPa $\pm$ 0.7 MPa	20.9 MPa	450%

Table 2: Nominal coating thickness of polyurea.

Tube	13	14	15	16
Coating Thickness, mm	3.9	4.1	2.9	7.3

3 Summary of Experimental Results

The data gathered falls into three regimes: purely elastic deformation (all tubes), plastic deformation resultant from a reflected detonation of initial pressure 200 kPa (tubes 9, 13, and 15), and plastic deformation resultant from a reflected detonation of initial pressure 300 kPa (tubes 10, 14, and 16). The complete set of data will be discussed in the presentation. Herein, we restrict ourselves to examining the effect of polyurea on hoop strain data.

Figure 2 shows the effect of polyurea on elastic strain; the vertical offset of strain data is proportional to the physical separation of the gauges along the tube axis. The initial rise in strain reveals the arrival of the incident detonation traveling at the theoretical Chapman–Jouguet speed. The arrival of the reflected shock wave results in additional strain but, for this low initial pressure, the second rise in strain is lost in the elastic oscillation of the tube wall. We see that the addition of polyurea significantly affects the peak-to-peak oscillation height and slightly affects the oscillation frequency. The viscoelastic properties of polyurea are the likely source for the decrease in oscillation height. The reduced frequency is most likely caused by the added mass of the polyurea—the additional mass would suggest a 14% decrease in frequency which is very close to the 13% reduction observed. The mean strain at each gauge location is largely unaffected by the addition of polyurea suggesting negligible strain mitigation for small strains.

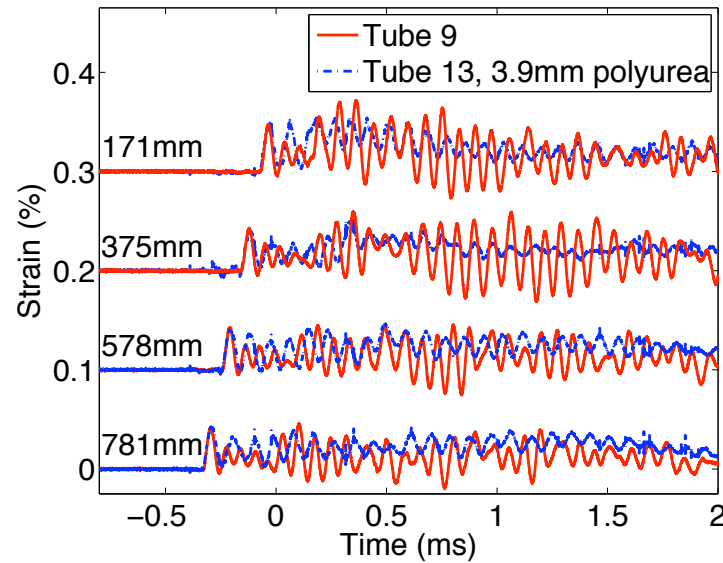


Figure 2: Hoop strain data for a detonation of initial pressure 50 kPa resulting in purely elastic strain.

Turning now to plastic deformation, Figures 3(a) and 3(b) reveal how polyurea affects plastic strain caused by a reflected detonation of initial pressure 200 kPa. Similar to the elastic case presented in Figure 2, the initial rise in strain reveals when the incident detonation arrives. The second rise in strain shows when the reflected shock wave arrives. It is this reflected shock that results in the largest pressures and hence the largest strains as discussed in [6]. Figure 3(a) portrays the damage mitigation potential of polyurea wherein a 3.9 mm polyurea coat mitigated the maximum measured outer diameter by 8.7% and a 2.9 mm coat by 14.3%. It is especially surprising that the thinner coat had the greatest effect on the peak deformation. This may suggest that the damage mitigation mechanism is more complicated than structural reinforcement and added mass, or it may indicate that the strain gauge wires (which ran underneath the polyurea in tube 13) served to lessen the effect of the polyurea layer. Figure 3(b) shows that, although the strain is lessened, the general shape of the strain signals is largely unchanged by the addition of polyurea, except for regions very near the reflecting end where the increased bending length for the tube with polyurea becomes significant.

Analogously to Figure 3, Figures 4(a) and 4(b) portray strain and final outer diameter data from detonation experiments of initial pressure 300 kPa. Much of the same quantitative and qualitative observations that apply to the 200 kPa initial pressure case also apply here. The primary exception is that, in this case, the final outer diameter is reduced more for the case of a thicker polyurea layer (although the precise thicknesses used in the 200 kPa experiments were not reproduced here). The 4.1 mm layer resulted in a peak strain reduction of 11.3% and the 7.3 mm layer resulted in the largest strain reduction of 20.5%.

4 Description of Numerical Setup

Akin to the analysis discussed in [6], LS-DYNA has been utilized to compare the experimental results discussed above with a realistic finite-element model. Realistic material models that incorporate strain-rate effects will be employed (such as discussed in [10, 11] for stainless steel and [12–14] for polyurea). Results of the numerical comparison will be included in the final presentation.

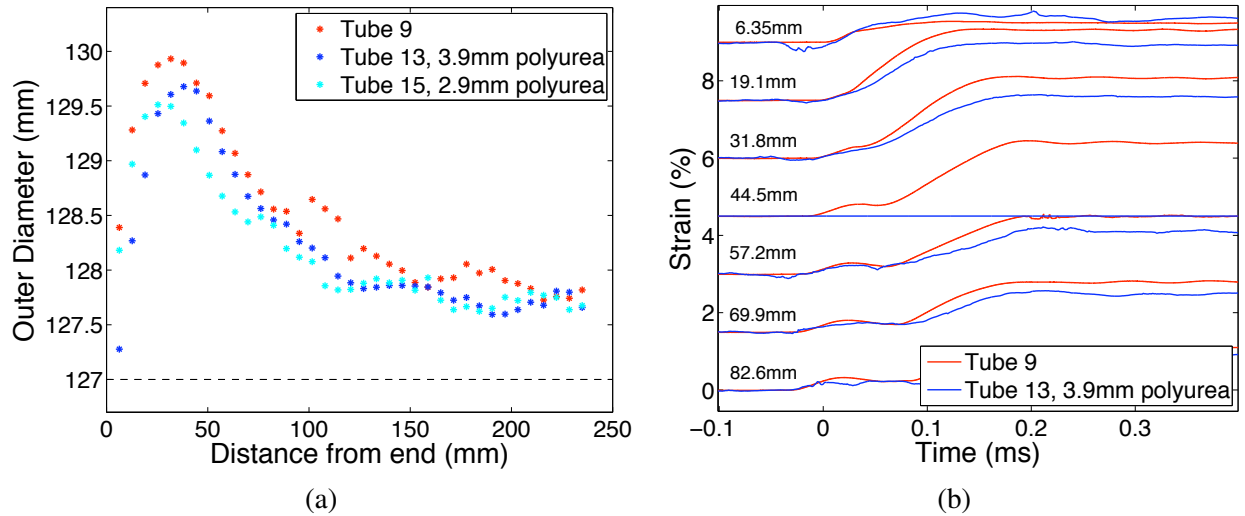


Figure 3: (a) Final outer diameter and (b) strain data for detonations of initial pressure 200 kPa. The flat line for the tube 13 strain gauge at distance 44.5 mm indicates failure of this strain gauge during testing.

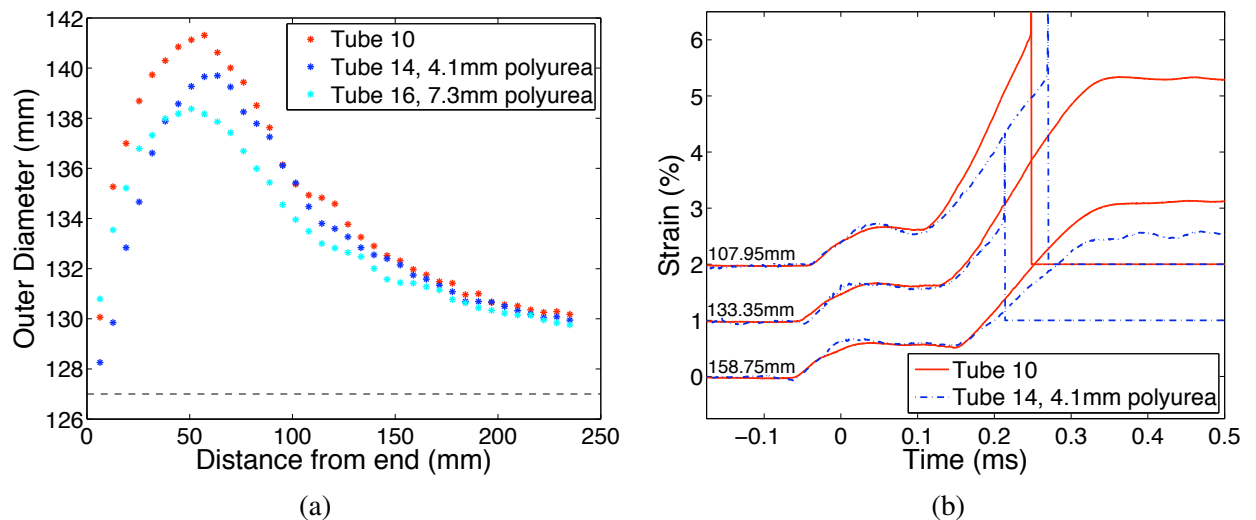


Figure 4: (a) Final outer diameter and (b) strain data for detonations of initial pressure 300 kPa. The large strains resulted in failure of all strain gauges as indicated by the rapid drop to zero strain.

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